Post-Disaster Reconstruction of Cultural Heritage: Citadel of Bam, Iran

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Bam Project started suddenly after the earthquake on December 26, 2003, that collapsed an important cultural heritage in south-east Iran, Citadel of Bam. This paper briefly summarizes our nearly eight years of effort for post-disaster reconstruction of Bam Citadel. The paper starts with the framework of the project that consists of architectural process and conceptual process and we discuss the design of workflow for efficient reconstruction process. Architectural process is discussed in terms of accuracy requirement of modeling, comparison of manual, semi-automatic and automatic modeling, and rendering of the model using a 3D CG tool such as 3ds Max. Conceptual process is also discussed in terms of designing our knowledge about Bam using ontology, and Web framework for navigating the knowledge base.

1. Introduction

The start of Bam project was all of a sudden. When Bam, an old city in south-east Iran, was struck by a strong earthquake on December 26, 2003, the cultural heritage of Bam was almost completely collapsed to become the debris of mud brick. We were shocked by the damage of Bam, and strongly felt that we should do something for Bam. This is the moment when Bam project had suddenly started.

We immediately released the Website [1] on December 31, 2003, just after five days of the earthquake. We wanted to raise public awareness to the disaster of Bam, and to start voluntary data collection by asking people for sending photographs and videos taken before the earthquake. At the same time, we also made contacts with various institutions in Iran and in other countries to ask for pre-earthquake data. Nearly eight years have passed since the earthquake, and we have made some progress in the post-disaster reconstruction of Bam. The purpose of the paper is to summarize the result of our project after the earthquake, and to learn lessons from our experience on post-disaster reconstruction.

The city of Bam was on the ancient route of Silk Road, and is also known to produce good date palm trees. The historical citadel of Bam had been evolved to a large mud brick complex, and was known to be one of the largest mud brick structures in the world. The size of the citadel is about 200,000 square meters, and kept many typical aspects of Persian architecture. The citadel was later abandoned and eroded by the weather. To deal with the destruction of the historical building, the restoration of Bam Citadel had been making a progress before the disaster, but the earthquake completely ruined the result of restoration. One year after the earthquake, "Bam and its Cultural Landscape" was inscribed on the list of World Heritage in Danger by UNESCO, but the physical reconstruction of Bam Citadel is still slow compared to the size of the citadel. We focus on an alternative scenario; to reconstruct Bam Citadel virtually in the cyber world with sufficient and satisfactory documentation to be used in physical reconstruction.

Post-disaster reconstruction posed many challenges to our team. The sudden launch of the project was simply driven by our enthusiasm for contributing to disaster recovery using our skills. We did have some knowledge about and connections to Bam before the earthquake, but we were not well-prepared for the project, and did not have any learning phases or feasibility studies in advance. Our research has been making progress in a trial-and-error manner for eight years, and we believe that now is good time to share and generalize our experience with other post-disaster cultural heritage reconstruction activities.

The paper is organized as follows. Section 2 describes voluntary and institutional data collection activities which are indispensable for post-disaster reconstruction. Section 3 explains the basic framework of the project with proposed workflow to keep the quality of documentation. Section 4 describes the architectural process for modeling and rendering, with a focus on manual, semi-automatic and automatic modeling. Section 5, on the other hand, describes the conceptual process for modeling and rendering of knowledge related to Bam. Finally Section 6 concludes the paper with our idea on future work, and also with our thought on post-disaster reconstruction.

2. Project Overview

2.1 General Framework

The purpose of our post-disaster reconstruction is to make an archive of accurate documentation of Bam Citadel to satisfy the accuracy level required for research purposes and physical reconstruction. For this purpose, the following issues need to be studied; 1) digitization of the physical world into the cyber world, 2) modeling and rendering in the cyber world, 3) implementing virtual model in the physical world. Figure 1 illustrates the structure of the project with three processes above. Post-disaster reconstruction of cultural heritage faces the problem of data sparseness because the cultural heritage is already gone, and new data cannot be obtained from measurement-based techniques. Hence data collection activities to make heterogeneous data archives play an important role to achieve high quality reconstruction. This issue will be discussed in Section 3.

After making heterogeneous data archives, we need to make a model of cultural heritage as the basis of post-disaster reconstruction. Our task can be classified into two types of processes, namely the architectural process and the conceptual process. Both processes can be further divided into two processes, namely modeling and rendering. Modeling takes data as input, and creates a model that represents the structure of information. Rendering, on the other hand, takes a model as input, and creates an output which visualizes the structure of information.

The architectural process deals with the structure of the building in the form of wireframe. Surface and texture is also added to the wireframe to represent the complete structural information of architecture. The model is then rendered in the form of multimedia content such as images and videos by controlling the appearance of architecture using parameters such as illumination. The conceptual process, on the other hand, deals with the knowledge of the building in the form of ontology. Model represented as ontology can be managed by a suite of software tools and formats, such as RDF (Resource Description Framework), RDBMS (Relational Database Management System), and CMS (Content Management System).

The final process is to implement the virtual model in the physical world. The first possible path is to use our model directly as a draft for physical reconstruction. The draft can be used for a building-level reconstruction, or even for a city-scale reconstruction. The second possible path is to use our model in a museum on the site as the prototype of physical reconstruction. More advanced idea is to regard Bam Citadel as a field museum, in which a visitor can use augmented reality (AR) devices to see the overlay of virtual buildings on the real scene.

2.2 Modular Design of the Workflow

When we started to work on the reconstruction of Bam, we formed a team of computer graphics (CG) experts and domain experts such as architects for the 3D modeling of architecture. In the first phase, CG experts are in charge of both modeling and rendering processes, and domain experts gave instruction for making models, and checked the result to ask for correction. CG experts have knowledge about modeling and rendering of architecture, so we thought this is a natural choice for the workflow. But we realized that this is not a good choice, because we were all frustrated by the large communication cost required in the team.

What actually happened is as follows. The modeling was not a trivial task of manipulating the software, but actually required domain experts' knowledge about Persian architecture. This is because in post-disaster reconstruction, the estimate of missing information requires the proper interpretation of heterogeneous data in an integrated manner, but this is a high-level task which can only be done by domain experts. Even if domain experts tried to transfer their interpretation to CG experts through instruction, CG experts did not have knowledge behind instructions. An accurate shape for historic adobe architecture could be drawn only when they know the meaning of the shape.

To solve this problem, we established the following procedure. Firstly, domain experts prepared evaluation reports with hundred pages, took snapshots of 3D models with errors annotated on the snapshots, compared them with photos, and explain CG experts clearly in reports where to make corrections. Secondly, CG experts read the evaluation reports, corrected 3D models, took snapshots of the corrected components and answered by correction reports to domain experts. We made 3D models for 10 major buildings by this method, but we realized that this method was very time consuming. So we decided to introduce a more efficient method in the second phase.

The new workflow was designed such that domain experts worked on the modeling process, while CG experts worked on the rendering process. In this case, the transferred from domain experts to CG experts was the model, not the knowledge or instructions. The rendering process also needs domain knowledge, but it is less critical than the modeling process. As a result, the new workflow greatly improved the efficiency of the process. We completed the process in much less time, or we could even complete the model that we could not complete in the 1st phase.

This observation suggests that we need to establish a modular design of the workflow with careful thought on who should work on which part of the project. Those two processes require different skills, tools, and goals. The modeling process requires the skill to estimate the missing information of architecture, while the rendering process requires the skill to control the appearance of architecture. The tool they use is also different; the former uses a CAD (computer-aided design) tool (AutoCAD) to make a wireframe model, while the latter uses a 3D CG tool (3ds Max) to make multimedia content such as images and videos. The goal is also different; the former focuses more on accuracy, while the latter focuses more on appearance.

Note that this situation is different from pre-disaster reconstruction, or reconstruction under a normal situation, where measurement-based techniques such as laser scanning [2] can be applied for creating 3D models. Higher accuracy can be achieved by objective measurements without domain experts' knowledge, and this suggests that there is less reason to separate modeling and rendering processes in an explicit manner. However, we suggest that the fundamental reason of separation is not only for data sparseness, but also for the division of roles. As will be explained in Section 5, conceptual process can also be understood as the separation of modeling and rendering. In a similar sense with the separation of model and view in software engineering, the modular design of workflow reduces the complexity of each process and the communication cost in the team.

3. Data Collection Activities

3.1 Voluntary Data

Figure 2: Voluntary collections of photographs.

As introduced in Section 1, we launched the Website just after five days of the earthquake. This is because a quick response is important for disaster recovery to catch the maximum awareness of people shortly after the disaster. We took that opportunity to send requests for help to people who can provide us with many kinds of data before the disaster. The requests were posted on the Website and also on e-mails to ask for 'information volunteers' for data collection. Our requests gave an impact on people who had past experiences with Bam. Hundreds of photographs and a few videos were sent to us from tourists who have visited Bam before the earthquake, as Figure 2 shows. We added basic metadata such as title and place to photographs and videos, and put them on the Website to share with other people.

Voluntary data collection is important for post-disaster reconstruction, because data sparseness may be the most critical limiting factor for the quality of post-disaster reconstruction. This makes a fundamental difference from pre-disaster reconstruction, where we can repeat measurements when necessary. Although this problem cannot be solved in general, the world is getting better, however. Voluntary data collection is strongly supported by the advance of digital technology. As digital imaging sensors such as digital cameras, smart phones, and video cameras are getting popular and ubiquitous, it is more likely than before that some people already have data we need. The problem here is to build a well-known platform to connect people and the project for extensive data collection. Our platform had limited power, but contributed to the collection of data from volunteers in the world.

The world is changing more. Compared to the situation in 2003, when the project started, the growth of online photo sharing sites makes it easier to search a large amount of photographs about cultural heritage. Social media has also become a well-known platform for sharing data. If the earthquake would have happened now, we might have searched for photo sharing sites to collect more data (under an appropriate Creative Commons license). People who posted photographs on social media are not explicit volunteers, but are implicit volunteers who can help us with the variety of data.

3.2 Institutional Data

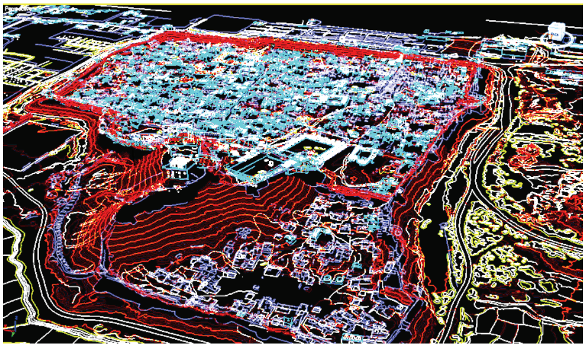

Figure 3: Photogrammetry map of Bam Citadel. (IFCA Agreement lead by Prof. C. Adle from CNRS).

We also tried to collect data from various institutions in Iran and in other countries. This type of data includes 2D drawings, aerial photographs, on-site photographs (Partly provided by Iranian Cultural Heritage, Handicraft and Tourism Organization), and the photogrammetry map (provided by Prof. Adle from CNRS as Irano-French Cartographic Agreement). We also obtained Quickbird high resolution satellite images taken before and after the earthquake. Among the data collected, the photogrammetry map (Figure 3) is the most basic and useful data, because it can gives information about the terrain of Bam Citadel, which represents the rough estimate of the location and height of buildings like digital elevation model (DEM). The photogrammetry map and high resolution satellite images are also used for manual modeling as a reference for the accurate positioning of 3D models. The photogrammetry map also provides a rough 3D model in semi-automatic modeling. Other important institutional data includes interviews with experts. Their memory may not be quantitative, but qualitative information can be reflected into the model for manual modeling.

4. Architectural Process

4.1 Requirement of Accuracy

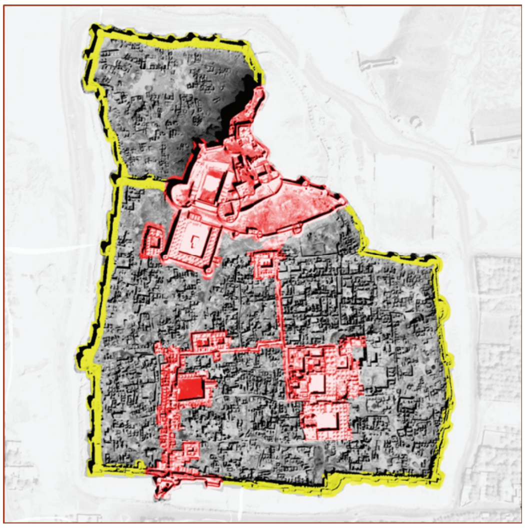

Figure 4: Requirement of accuracy for Bam Citadel; color-coded (red: highest accuracy).

As stated in Section 1, our model should be accurate enough for research purposes and physical reconstruction. Accuracy here includes not only the correctness of size but also the appropriateness of structure as Persian architecture. Under post-disaster reconstruction where new measurements are not allowed, our focus is on how to achieve high accuracy with limited cost and time [3].

The constraint can be paraphrased as finding good balance between accuracy and cost. Ideally we want to make an accurate model for the whole city, but it is not feasible for the following reasons. Firstly, the size of the city, and the number of buildings within it, makes a city-scale manual modeling unrealistic. Secondly, available data is biased towards important buildings or tourists' attraction, and less important buildings have less documentation. Even time and cost is affordable, accurate modeling of many unimportant small buildings is unrealistic.

Hence we decided to divide the city into three areas based on the requirement of accuracy. The area that requires high accuracy includes about 10 important buildings in the city, and we applied manual modeling to achieve high accuracy by investing resources. The area that requires moderate accuracy includes surrounding walls, and we applied semi-automatic modeling for the reduction of cost with the help of computer algorithms. Other areas requiring low accuracy includes unimportant buildings in the city, and we tried semi-automatic or automatic modeling for minimizing resources. We then merged all models created by three approaches after accurate positioning on the photogrammetry map, and finally obtained the 3D model of Bam Citadel.

4.2 Manual Modeling

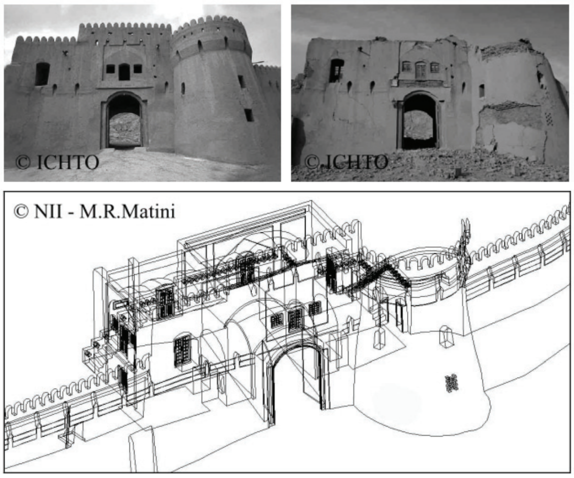

Figure 5: Photographs and the wireframe model of Second Gate. Source: Iranian Cultural Heritage, Handicraft and Tourism Organization.

In post-disaster reconstruction, estimating missing information from available heterogeneous data is the most difficult part of the modeling process. We represent our estimate of the original shape in the form of a wireframe model. Firstly we tried to develop a precise 2D drawing with all the necessary information for the 3D modeling. This solution, however, turned out to be inappropriate because the free-form architectural elements of the adobe constructions in Bam Citadel cannot be easily represented by 2D drawings. In many cases, we needed several plans, sections, and elevations to get an understanding of the space. Finally we found that the best solution was to develop a 3D drawing for the geometrical character of a complicated adobe construction in three dimensions.

Although heterogeneous data consists of appropriate 3D information about the buildings, it still had ambiguities and other problems. For example, there were dimensional incompatibilities between different 2D drawings and errors in their coincidence with the photogrammetry map and photographs. The available 2D drawings for recognizing the complete shapes of buildings were insufficient; different on-site photos taken from the same angle show various periods of restoration, and they needed to be prioritized in the 3D modeling process. In addition, there were few photos of interior spaces and less important buildings, and the photos were mostly of low resolution. The scale of the aerial photos was not fine enough for recognizing small elements, and the facades were usually not visible. The photogrammetric map had to be modified and its lines adjusted before it could be used for 3D modeling. Finally, there are no oral or textual references about several parts of the Citadel.

Ambiguities and other problems led us to experts who are familiar with historical mud brick architecture in Persian desert cities and also have knowledge about 3D modeling. These experts could comprehend the content of our process and knew the chronology of the data and the original shapes of the buildings. The drawing is developed in a process with different stages of modifications. A 3D drawing initially drawn from the heterogeneous data and completed through geometrical, structural, proportional, and detail modifications was then refined for the final model.

But we still did not have sufficient pre-disaster information showing the original shape or with which we could estimate the proportions for a complete 3D drawing of the building. The only possibility for recovering the original shape, proportions and details of spaces was to study the relics that survived the quake. At the beginning of modeling, it was agreed that the 3D models should be based on the last renovation of the buildings. For this reason, we used the relics as complementary information. There are two ways to use relics: directly or indirectly. Sometimes a space, detail, or part of a building remains and we could complete a 3D drawing by directly inspecting it. Although the Bam Citadel was devastated, parts of several buildings, in particular, the layout of the ground floors remained intact.

Our interpretations of the relics were classified according to symmetry, construction method, and renovation period. Firstly, symmetry plays an important role in historic Persian architecture. Because of structural and aesthetic aspects, symmetry can be observed not only in architectural elements such as walls, roofs, windows, etc., but also in the whole composition. Secondly, the characteristics of materials, such as mud brick, wood, and stone, define the specific method of construction, and there is a close relationship between material, construction method, and shape. This relationship can help us to recover the original shapes of destroyed elements such as arches, vaults, domes, openings, niches in walls, windows, and doors. Thirdly, the renovation period and renovation group had characteristic details, and these similarities helped us to guess the detail of destroyed parts from the details of surviving parts [3].

Figure 5 shows the situation of the Second Gate of the Citadel before and after the earthquake, showing wireframe and photographs. Due to the limitation of space, we skipped the detail of the manual modeling [3, 4].

Figure 6: Rendering of 3D models from semi-automatic modeling using 3ds Max.

4.3 Semi-Automatic Modeling

For areas that require moderate or low accuracy, we want to automate the modeling process to reduce time and cost for reconstruction. Our proposed method for semi-automatic modeling is to refine the photogrammetry map toward the 3D models of unimportant buildings and paste texture from tourist photographs on the 3D models [5].

We started from refining the spline contours of the photogrammetry map and estimated which spline contour represents the wall of buildings. We then applied an extrude filter to the spline to add a vertical surface (wall) that surrounds the building. Some of the spline contours were judged as ground, so flat or slope surface was added to them. The final 3D model was the mesh that represented the buildings and grounds of the Bam Citadel.

We then moved to the rendering process. Texture was obtained from photographs taken before the earthquake. Firstly we roughly searched for the camera location of a photograph by comparing the scene of a virtual camera for the 3D model and the photograph taken by a real camera. We then compared the boundary between the sky and buildings on the two images, and improved the matching of camera parameters. This process was done manually on a 3D CG software (3ds Max), but the mapping of photographs on the 3D model using projective geometry was done automatically. We repeated the mapping of photographs on the surface mesh to use photographs as texture. Most of the algorithms were implemented on 3ds Max using Maxscript, and some image processing algorithms were implemented on Matlab.

Figure 6 shows the result of rendering from semi-automatic modeling, in which the whole city of Bam is visualized. As the result shows, this is a simple method to produce a city-scale 3D model, but we need to solve the following problems to make it as a practical algorithm. Firstly, surface mesh created from the extrude filter is often not correct. As introduced earlier, the resolution of the photogrammetry map is limited, and buildings are represented in vague forms on the map. The semantic annotation of spline contours is also limited, so we need an intelligent algorithm to classify the architectural role of each spline (such as wall, ceiling, dome, etc.). Secondly, texture obtained from photographs suffers from illumination change. Photographs taken at noon and in the evening have different illumination conditions even for the same scene, so color of photographs should be calibrated and standardized to reduce the effect of illumination change. This has been an important research topic in computer vision, and we need to develop an algorithm that fits to this situation.

4.4 Automatic Modeling

Automatic modeling is about algorithms that require minimum human intervention. We tested two approaches, namely 3D reconstruction from multiple images based on point correspondences, and 3D reconstruction from videos using structure from motion algorithm [5]. We tested those algorithms, but we were not successful at this moment because of the following problems.

For the former algorithm, multiple images were taken by different cameras at different times, and this is a difficult situation for the algorithm due to little control for image capturing. Moreover, the number of available images was too small to solve this problem. For the latter algorithm, the problem was in the quality of the video, which was taken about 30 years ago from a helicopter. Degradation of the film, camera control such as zooming in and out, unstable framing due to the motion of the helicopter; all the factors make the problem more difficult to solve. Because of this situation, automatic modeling is still not our choice in our modeling process.

4.5 Architectural Rendering

The 3D models created by manual / semi-automatic / automatic modeling were merged at correct positions to be a unified 3D model of Bam Citadel. Visualization of the model required the following steps. First we added surface and texture to the wireframe model if absent. Simple mud brick and ground texture was added, considering balance between reality of texture and computation time. We then configured a sequence of scenes with proper illumination to create images of buildings or walkthrough videos to visit many places in the Citadel. A 3D CG tool (3ds Max) with an appropriate choice of a rendering engine has generated multimedia content such as images and videos, which were finally released on the Website. Figure 7 shows one of the latest walkthrough videos that we released on the Website.

The problem of images and videos as the output of rendering is that they lack interactivity to navigate through the 3D model. One solution is to use Quicktime Virtual Reality (VR), which allows users to look at different direction with variable resolution. But interactivity offered by Quicktime VR is still limited, because users cannot move from the camera location to another point. More advanced mechanism is to use virtual reality system for real-time rendering. We used OmegaSpace VR presentation software with head mount display (HMD) such as 3DVisor to test the effectiveness of VR technology for our model. But the fundamental limitation of the VR system is that you need to go to the place where the special device is available. It may be useful for museums, but it is not a good solution for the general public.

The best solution is to build a system on the Internet where users can interactively navigate through the 3D model at any time from any place in a browser. We do have a simple solution. Using VRML (Virtual Reality Modeling Language), anyone having a VRML browser can download the data and interactively render the 3D model. But this solution is not acceptable in our case, because the protection of the original model is not considered in the VRML solution. The ideal solution is to protect the original model in the server side, but only transfer the rendered output to the client side in an interactive manner in real-time. We are now seeking for a solution to realize this idea.

Figure 7: Rendering of 3D models from manual modeling using 3ds Max.

5. Conceptual Process

5.1 Conceptual Modeling

In comparison to the architectural process, the conceptual process focuses on concept, or our knowledge about Bam Citadel. Conceptual modeling is about representing our knowledge about cultural heritage and various project-related information such as people, process and outcome. We also need to maintain links with heterogeneous data so that data

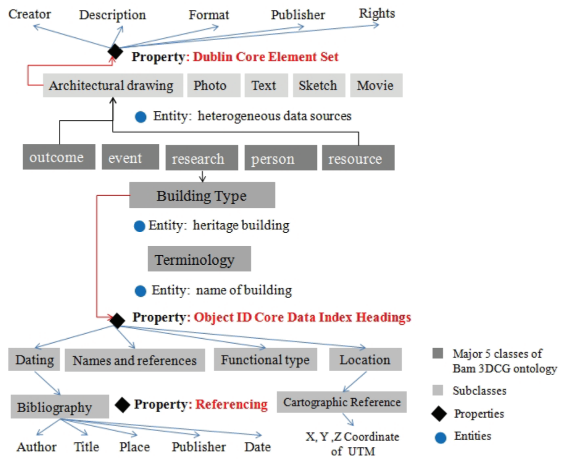

Figure 8: Architecture of Bam 3D CG ontology.

can be explained with semantic annotation which is linked with various concepts associated with data.

We developed Bam 3DCG ontology for this purpose. Figure 8 shows a part of Bam 3DCG ontology [7]. The ontology represents the typology of buildings in Bam and also organizes the information infrastructure associated with Bam project. The ontology is designed as a multilingual ontology because people from several countries are involved in the project (such as Iran, Japan and France). Some of the project information, such as members, inputs, outputs, and bibliographic information is also integrated. About metadata schema, we maximize the usage of international standards to respect interoperability. Firstly, we used a part of the Core Data Index of Object-ID for the heritage-building domain (Historic Buildings and Monuments of Architectural Heritage) [8]. We used nine headings such as names and references, location, functional type, dating, and selected some subclasses. Secondly, Dublin Core is used for annotating visual data such as photograph and video with creators and contributors. Thirdly, UTM (Universal Transverse Mercator) coordinates and WGS84 latitude and longitude are used for representing geographic coordinates.

Ontology was designed and edited using ontology editor Protégé. We used it to input data and export the result as RDF. Protégé is a convenient tool to manage ontology and RDF, but we also felt some problems when we used the tool for our project. The most critical one is the lack of built-in mechanism to manage multimedia content such as images, videos and CG models. It can maintain an ID which is a pointer to the content (such as a filename in the local machine, or a URI to content when it is already accessible on some Websites), but it is not designed as an integrated content management system. We need a better mechanism in this regard.

5.2 Conceptual Rendering

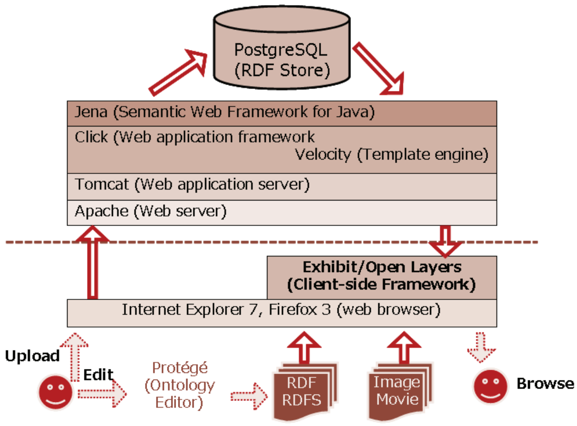

Figure 9: Architecture of conceptual rendering engine.

The RDF output exported from Protégé is treated as a model of our knowledge and our conceptual rendering engine (Figure 9) make it accessible on the Website on which users can navigate through our knowledge base. We developed Bam3DCG Website [9] on the fifth anniversary of the earthquake, namely December 26, 2008. This Website uses Jena as semantic Web framework, PostgreSQL as RDF store, and Web application framework (Tomcat / Click) for rendering HTML. The combination of these open source tools is enough for managing and rendering the knowledge base. The website includes not only architectural knowledge about Bam, but also project information organized in a class hierarchy. It can also render the map of buildings on the site so that users can access to building information from the map.

This framework can be understood as the separation of conceptual modeling by domain experts (ontology), and conceptual rendering by software engineers (system). The design of ontology usually requires high-level knowledge about the target domain (Persian architecture), but after the knowledge is represented by ontology, the subsequent processes can be done by software engineers who know better about system design.

In the future, we can refine the ontological model to accept other metadata schemas, improve the software architecture for better separation of modeling and rendering, and update our system to follow linked data principle, where resources in the knowledge base are linked with knowledge in the world as triples. We can take advantage of the fact that the system is already built on RDF.

6. Conclusion and Future Work

This paper summarized our eight-year effort for the reconstruction of Bam Citadel. This project suddenly started just after the disaster, without preparation in advance, and we had to overcome many difficulties we encountered after we started the project. But we think that a disaster recovery project is like this; it tends to share the same difficulty, because we cannot be prepared enough for future disasters. Something unexpected always happens.

On March 11, 2011, we are shocked by massive destruction in Tohoku and Kanto regions in Japan, and this disaster caused similar situations with the disaster in Bam. Many cultural heritages were lost in tsunami, and efforts have been put into the recovery of damaged cultural heritage. As Bam Project indicates, however, the revival of cultural heritage takes a long time and much effort. We still believe that it is worth doing it, because the recovery of cultural heritage is related to the memory of people, and the pride of the community. This is why the reconstruction of cultural heritage from disasters, both natural and man-made ones, is considered as an important post-disaster activity. The purpose of the reconstruction project is not only for doing research, but also for making a monument that symbolizes the recovery of the community.

For this reason, it is always important to make our results publicly accessible so that people can feel the sense of recovery from the disaster. We will see many disasters in the future, so we need to share knowledge about how to prepare for the disaster. For the short term goal after the disaster, we need to know how to raise awareness, share information, and start data collection activity for preservation. For the long term goal, we need to know how to reconstruct cultural heritage, and revive memories of the community using the monumental cultural heritage.

Future work includes semi-automatic modeling of remaining parts to make the 3D model of the whole city, interactive rendering of 3D models through the Internet (WWW) while protecting original 3D models from users, and linkage between architectural and conceptual processes for the 3D semantic database.

Acknowledgment

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